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学位論文題目	Study on material removal mechanism in rotary in-feed grinding （ロータリーインフィード平面研削における材料除去メカニズムに関する研究）
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論文内容の要旨

Rotary in-feed grinding is a most promising process with high efficiency, precision and controllability of wafer geometry including the thickness and flatness and thus has been widely used in manufacturing of monocrystal wafers, such as silicon, silicon carbide, sapphire, lithium tantalate and etc.　In order to deeply understand the material removal mechanism in rotary in-feed grinding, the objectives of this research are:

1. Theoretical and experimental investigations on the wafer profile generation.

2. Theoretical and experimental investigations on the wafer topography generation.

3. Theoretical and experimental investigations on the grinding force and heat assessments.

The thesis consists of the following contents:
In Chapter 1, monocrystalline materials are briefly introduced together with their applications and manufacturing processes.　The conventional manufacturing process such as lapping and polishing using free abrasive is no longer able to meet the requirements in cost, productivity and accuracy. The fixed abrasive process (or grinding) stands out as a most promising manufacturing technology to replace the conventional processes.
The rotary in-feed grinding dynamic originated for wafering process is relatively new and totally different from that of conventional grinding.　This thesis provides a deeper insight view of mechanism of rotary in-feed grinding, from engineering perspectives of 1) wafer profile and geometry, 2) chip formation and wafer surface topography and 3) grinding statics and dynamics.
A detailed survey on the monocrystalline wafering process has been made in chapter 2.　From accessible literature works, it is revealed that most of published researches are focusing on the three specific scoops including the total thickness variation (TTV), surface integrity and subsurface damage to evaluate the performance of rotary in-feed grinding.　When the dynamics of rotary in-feed grinding is concerned, the grinding performances should be assessed from the following aspects: (1) Kinematics and path control of each cutting edge which govern the wafer shape and profile; (2) Chip formation and protrusion distribution of cutting edge which govern the surface topography and integrity; (3) Grinding force and grinding heat which dominate the subsurface damage.　Therefore, a full understanding of rotary in-feed grinding mechanisms become more essential.
The mathematical analysis and experiments for wafer profile generation are described in chapter 3, to obtain and optimize the grinding conditions for achieving great wafer geometry.　First, the motion and path of cutting edge in rotary in-feed grinding are kinematically analyzed in three-dimensions, to address the behavior of each abrasive in generation of the wafer profile.　The results mathematically reveal the effects of wheel specifications, grinding conditions and wheel/wafer configurations on the wafer geometry, particularly including offset distance between the axes of wheel and wafer, the tilt angles of wafer axis and the diameter of the wheel.　Second, the effects of both cutting path density and machine stiffness on the wafer profile are assessed.　The experimental results in Si wafer grinding demonstrate a solution using tilt angle to counterbalance the effects of machine stiffness and cutting path density on the wafer geometry.
In Chapter 4, the surface topography on the wafer surface is associated with the chip formation which highly depends on distribution of abrasive protrusion in height-wise.　Both theoretical

analysis and experiments results lead to a fact that the surface roughness becomes larger toward to the outer circumference of the wafer, but smaller as decreasing in the rotational speed ratio. In addition, influence of depth of cut has also been investigated. The mathematical analysis results suggest that inadequate depth of cut may not improve the surface roughness in rotary in-feed grinding due to the insufficient effective cutting edge involved in material removal.

The statics and dynamics in rotary in-feed grinding have been studied and discussed in chapter 5, in order to associate not only the grinding conditions but also the wheel specifications with the grinding force, grinding power and grinding heat. The grinding force exerted on an individual abrasive is first correlated to the chip cross section, and then extended to the grinding force on a single wheel segment and whole wafer. Meanwhile, a wireless thermo/dynamo-meter is designed, developed and applied to measure the grinding force and grinding temperature simultaneously during the grinding process. Both theoretical analysis and experiment results tell that the grinding force on a wheel segment was proportional to the segment length, gradually grew along the wafer radial distance and rapidly dropped to zero when the wheel segment exited from the wafer fringe. Grinding force and consumed grinding power are proportional to the square of the wafer size. This fact suggests that grinding large diameter wafers requires high rigidity and the spindle power of the grinding machine.

Chapter 6 makes the summary of the achievements obtained in this study.

論文審査の結果の要旨

本研究は，ロータリーインフィード平面研削における材料除去メカニズムの解明を目的とし，ウエハの形状創成，ウエハ表面トポグラフィ（表面粗さ）および研削中の抵抗・動力の３つの課題に対して理論と実験の両面からアプローチした．

まず，研削中の個々の砥粒の３Ｄ運動軌跡を解析し，洗練された数式で表現し，加工条件や砥石仕様と関連付けた．幾何的な運動に砥粒軌跡密度および機械剛性の影響を取り入れ，研削で創成されるウエハの形状を高精度で予測できるようにした．また，実験結果との対照により得られた結果の妥当性も確認した．これにより，ウエハの形状創成に影響するパラメータおよびそれらの影響度合いを明らかにした．

次に，砥石表面に３Ｄでランダムに分布している砥粒を統計処理し，有効砥粒切れ刃の密度を割り出した．それぞれの切削切屑断面積より生成されるウエハの表面粗さを理論的に解析し，実測結果と比較・検証した．得られた知見は，高精度・高品位ウエハ加工を目指すにあたり，砥石仕様，加工条件の最適化の指針を提供するものである．

最後に，切削切屑断面積から個々の砥粒に作用する研削抵抗を算出し，同時作用する有効砥粒切れ刃について積分することにより，砥石セグメントおよびウエハ全体に作用する総研削抵抗と動力に関する理論式を導き出した．この理論式に対し，実際に使用する砥石のセグメント率および摩擦の影響を考慮した補正を行えば，実験と一致した研削抵抗および動力がモデリングできる．さらに，実測した動力の値に提案モデルを多関数フィッティングすることにより，砥石の初期の切れ味（砥粒先端角）の予測および砥粒摩耗の経時変化が記述できる．

申請者が本論文で取り組んだロータリーインフィード研削における材料除去メカニズムに関する研究は，今後ますます広く応用される単結晶機能材の加工において，工作機械の剛性，工具仕様ならびに加工条件の影響などを理論的に解明すると共に，得られた研究成果は，それらの設計，選定および最適化において極めて貴重な知見をもたらすものであり，新規性も高い．

申請者は，博士後期課程在学中に必要な単位を取得するとともに，本研究に関する成果を欧文学術誌論文１編（インパクトファクター付），国際会議論文２編として発表している．最終試験の質疑応答においても的確に答弁し，研究遂行能力と十分な専門知識を有すると判断した．学位論文審査会ならびに最終試験において，本学位論文はともに合格と判定された．以上を総合して，当審査会は，本論文が理工学研究科における博士学位論文の評価基準を満たし，合格と判断した．